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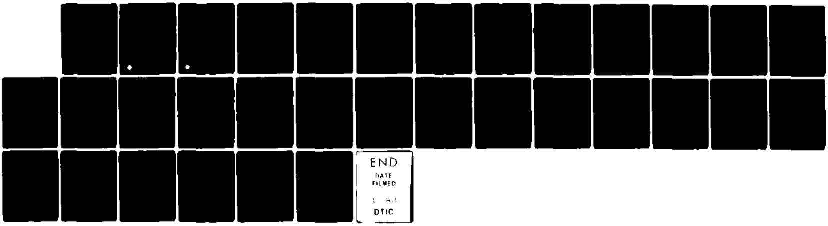

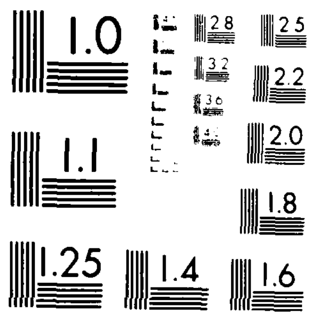

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FINAL REPORT

January 1, 1978 to December 31, 1982

ULTRAFINE-GRAINED SUPERCONDUCTORS

By

M. Ashkin, A. I. Braginski and J. R. Gavaler

Westinghouse Electric Corporation

Research and Development Center

Pittsburgh, Pennsylvania 15235

AFOSR Contract No. F49620-78-C-0031

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Both A15 and B1 structure superconductors with nearly optimum critical temperatures were prepared with a range of grain sizes down to the coherence length. In B1 compounds high critical current densities at high fields were obtained due to very large critical fields arising from a small column-void microstructure. Critical current data at low fields demonstrated that grain boundaries are not, invariably, efficient pinning sites. Extremely enhanced current densities were measured only in superconductors (B1) whose cross-

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sectional areas were made similar in size to a single vortex. No increase in critical temperature, which could be attributed to reduced grain sizes, was found. Reversible strain properties of B1 compounds were shown to be superior to those of the A15's. In both A15 and B1 compounds the reversible properties were independent of microstructure. However, a strong effect of microstructure on irreversible strain properties was found. The importance of impurities, particularly oxygen, in the growth of high-critical-temperature superconductors was demonstrated and hypotheses were proposed to explain the role of these impurities. Several other auxiliary topics involving high-critical-temperature superconductors were also investigated.

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1. Final Report, Ultrafine-Grained Superconductors

January 1, 1978 to December 31, 1982

AFOSR Contract No. F49620-78-C-0031

M. Ashkin, A. I. Braginski and J. R. Gavaler

2. ABSTRACT

Both A15 and B1 structure superconductors with nearly optimum critical temperatures were prepared with a range of grain sizes down to the coherence length. In B1 compounds high critical current densities at high fields were obtained due to very large critical fields arising from a column-void microstructure. Critical current data at low fields demonstrated that grain boundaries are not, invariably, efficient pinning sites. Extremely enhanced current densities were measured only in superconductors (B1) whose cross-sectional areas were made similar in size to a single vortex. No increase in critical temperature, which could be attributed to reduced grain sizes, was found. Reversible strain properties of B1 compounds were shown to be superior to those of the A15's. In both A15 and B1 compounds the reversible properties were independent of microstructure. However, a strong effect of microstructure on irreversible strain properties was found. The importance of impurities, particularly oxygen, in the growth of high-critical-temperature superconductors was demonstrated and hypotheses were proposed to explain the role of these impurities. Several other auxiliary topics involving high-critical-temperature superconductors were also investigated.

3. OBJECTIVES

The objectives of the 1978-1982 Westinghouse-AFOSR program, briefly stated, were:

1. To investigate the mechanism of critical-current density, J_c, enhancement in ultrafine-grained high-T_c superconductors.
2. To investigate the preparation of ultrafine-grained microstructures in A15 and B1 superconductors.
3. To determine the effect on critical temperature T_c of variations in grain size in A15 and B1 superconductors.
4. To correlate mechanical load properties and microstructures.

In addition, a general objective was to try to advance the understanding of high-T_c superconductors. Results obtained with this latter objective in mind, which do not fall under the specific headings listed above, are summarized in Section 4.5 under the general heading of "Other Topics." In each case more detailed discussions can be found in the publications which are listed in Section 5.

4. ACCOMPLISHMENTS

4.1 The Enhancement of J_c

In this program, much of the research was focussed on the investigation of the effect on J_c stemming from the formation of ultrafine-grained microstructures. Since microstructure can also influence the upper critical field (H_{c2}), which can in turn exert a strong influence on J_c, the effect of microstructure on this parameter was also studied. There are two classes of materials which contain most of the known high-T_c superconductors, namely the A15 and B1 structure compounds. All of the experimental work in this program involved these two classes of superconductors. The A15 structure materials studied included Nb_3Ge, Nb_3Ga, Nb_3Al, Nb_3Sn, V_3Si, and $V_3(Si\text{-}C)$. The B1 compounds studied were NbN and Nb(C-N).

4.1.1 Chemical Vapor Deposited (CVD) Nb_3Ge

The current-carrying capacities of CVD single-phase Nb_3Ge films and also films containing second-phase (Nb_5Ge_3) particles dispersed in the A15 matrix were investigated. By growing films of thicknesses varying in the 10^3 to 10^5 range and multilayered films, the A15 grain size and the Nb_5Ge_3 particle size and dispersion could be controlled. For Nb_5Ge_3 particle sizes of the order of d = 100 Å — i.e., approaching the coherence length of Nb_3Ge at 4.2K — effective flux pinning and very high J_c's ($\sim 10^9$ Amps/m^2 at 20T and 4.2K) were obtained. In single-phase Nb_3Ge, effective flux pinning was not observed even for very small grain sizes, of the order of 300 Å, obtained in the thinnest films and layers. Subsequent specific heat measurements indicated that this result was a consequence of near-surface and near-interface disorder and did not permit valid conclusions to be drawn on the strength of pinning on grain boundaries in these films.

4.1.2 Laser and Electron-Beam Annealed Nb_3Ge and Nb_3Sn

Critical current enhancement (up to 50%) was observed in thick (several μm's) CVD Nb_3Ge films which had been pulsed-laser-annealed. It was concluded that the J_c enhancement was caused by flux pinning on precipitated second-phase Nb_5Ge_3 particles in a small fraction of the unmelted portion of the film. Electron beam annealing was thus expected to produce a similar effect in a larger volume fraction of the sample, and to make the I_c-enhancement technically significant. The Karlsruhe Nuclear Center (KfK) e-beam annealing facility (PEBA) was used. Unfortunately, pulsed electron beam annealing of Nb_3Ge showed no improvements in J_c. It was apparently not possible to achieve the necessary combination of beam energy and pulse length to nucleate an optimum number and size of second-phase particles. The enhancement of J_c in beam melted and resolidified samples through the formation of an ultrafine-grained microstructure also did not occur due to mechanical damage of samples (see 4.2.1). Transmission electron microscopy (TEM) demonstrated, however, that *ultrafine-grained microstructures can be obtained* by e-beam annealing. This finding prompted a study of the effect of e-beam pulse annealing on a more stable A15 superconductor represented by Nb_3Sn layers on Nb substrates. Mechanical damage was reduced but not eliminated, so that the I_c-enhancement was not attained in Nb_3Sn as well. It was concluded that an upgrade of the PEBA facility would be necessary to solve the damage problem.

4.1.3 Sputtered Films on Heated Substrates

NbN and Nb(C-N) films were sputtered onto heated substrates held at temperatures from 450 to 1000°C. These films which have the B1 structure were deposited in thicknesses ranging from ~ 300 Å to several μm's and with grain sizes from ~ 80 Å to several μm's while maintaining T_c's close to the bulk value (~ 15K). In every case, regardless of type of substrate or growth temperature the films had columnar grains. In the case of films grown at relatively low temperatures ($\lesssim$ 500°C) there were voids between grains which extended completely through the film. Initially it was speculated that these voids formed only in films thinner than

~ 5000 Å. However, TEM data showed that they are present in films as thick as 2 or 3 μm. Both the size of the grains and the size of the voids become larger as the thickness is increased. In the absence of other imperfections, reducing the grain size had only a minimal effect on critical-current density. Films with grain sizes (column diameters) ranging from several microns down to a few hundred angstroms all had self-field J_c's of the order of 5×10^5 Amps/cm^2. A much higher self-field J_c (~ 2×10^6 Amps/cm^2) was, however, observed in films with grain sizes of $\lesssim$ 100 Å. In this case the voids were comparable to the coherence length. No peak in the (global flux pinning force F_p vs 1/d dependence was observed. Extremely high self-field J_c's were measured in NbN films which were fabricated into microbridges using photolithographic and sputter etching techniques. In the smallest NbN microbridge measured, which had a cross-sectional area of ~ 3600 nm^2, J_c (4.2K, zero field) was $\gtrsim 3 \times 10^7$ Amps/cm^2. This is the highest current density reported for any superconductor. The reason for this very high J_c is not entirely clear, however it must be in some way due to constraints placed on the motion of vortices by the smallest dimensions of the microbridge since the area of the microbridge is approximately the size of a vortex.

In addition to having high critical-current densities in self and low magnetic fields, NbN films were prepared which still maintained high J_c's in fields of 200 kOe and higher. This was due to the enhanced upper critical fields obtained in these films. Indeed among the more significant results obtained during the course of this program was the growth of NbN films having upper critical fields much greater than the theoretically calculated maximum H_{c2} for a bulk-like superconductor. The films showing maximum $H_{c2}(0)$'s of up to ~ 450 kOe (extrapolated to T = 0) have the above-mentioned column-void microstructure with lateral column dimensions ~ 80 Å and void dimensions ~ 20 Å. (Due to a misreading of the preliminary data a slightly higher maximum $H_{c2}(0)$ value of 500 kOe was initially reported in the July 1982 Semiannual Report.) Other NbN films with grain sizes of ~ 200 Å or larger have maximum $H_{c2}(0)$'s ~ 250 to 300 kOe which is consistent with the theory for bulk superconductors.

Because H_{c2} in the column-void film is also anisotropic with respect to the film surface, H_{c2} perpendicular to the surface being the largest, surface superconductivity (H_{c3}) nucleating at the surface of columns was proposed as the origin of the observed H_{c2}. However, as more data was obtained some modification of this interpretation was needed. A synthesis of all the data ultimately showed that the surface superconductivity interpretation is valid if the effect of the lateral column dimension, which is on the order of the coherence length, is included in the picture. This dimensionality effect on H_{c3} was previously observed in thin continuous films and calculated for films and cylinders. A theoretically derived H_{c2} vs temperature, based on the above ideas, fits the experiments over a wide temperature range. Data covering the temperature range $1.36K < T < 4.2K$ were obtained through cooperation with Prof. Ø. Fischer and Dr. M. Decroux at the University of Genève using a pulsed magnetic field facility.

4.1.4 <u>NbN Films Crystallized from the Amorphous State</u>

By sputtering niobium in an argon-nitrogen atmosphere using relatively low substrate temperatures and small target-substrate separation, X-ray amorphous Nb-N films were deposited in thicknesses varying from a few hundred angstroms to 6000 Å. After annealing at an optimum temperature of ~ 600°C these films crystallized into the B1 structure and were superconducting with T_c's of 15 to 16K. The crystallized films, deposited on sapphire substrates, have equiaxed grains with average grain sizes of ~ 300 Å as indicated by transmission electron microscopy (TEM). (More detailed discussion of the TEM data is given below in Section 4.2.) The current densities of these films were found to be no higher than ~ 8 x 10^5 Amps/cm^2 (at 4.2K and zero field). This value is not significantly higher than the ~ 5 x 10^5 Amps/cm^2 value measured in NbN films having an average grain size of > 1 μm. The J_c results in these films are thus similar to the data on NbN films having the column-void type microstructure, discussed above. This indication that grain boundaries may not always be efficient pinning sites, as is usually assumed, can be understood if, as proposed by Zerweck, grain boundary pinning is due to

the differences in the mean free path of the electrons in the grains compared to those in the boundary layers. In the case of these NbN films, calculations show that the mean free paths of the electrons in the grains are very similar to those in the boundaries, therefore the effectiveness of the boundaries as pinning sites is minimized.

3.2 Preparation of Ultrafine-Grained Microstructures

3.2.1 Thin Film Techniques

The most controllable way to prepare superconductors with a wide range of microstructures was found to be through the deposition of films of controlled thicknesses and at different temperatures. Both CVD and sputtering were used successfully. Using CVD, Nb_3Ge having grain sizes as small as 7[illegible] Å were prepared while still maintaining T_c close to the optimum value. Limited success in obtaining Nb_3Ge with an even finer microstructure was achieved by sputtering onto Nb_3Ir substrates. These latter results, however, were not consistently reproducible. Sputtering was used exclusively for the preparation of NbN and Nb-C-N films. T_c's near 15K were maintained in NbN films, less than 1000 Å thick, deposited on heated substrates. Such films were obtained by heating the substrates to the minimum possible value (~ 450°C) that would still permit the crystallization of the desired B1 structure. TEM studies showed that all of the films had a column-void microstructure. However, the dimensions of both the columns and the voids increased with increasing thickness. Therefore, only films of ~ 5000 Å and less exhibited the very high H_{c2} and J_c values reported above. In thicker films both the grains and voids became sufficiently large that no enhancement effects were obtained.

Another thin film method which was used to prepare ultrafine-grained microstructures was the controlled crystallization of B1 NbN from the amorphous state. With this method there was no dependence of grain size on film thickness. The grain dimensions were determined primarily by the annealing temperature and time. A TEM study of amorphous films deposited on either sapphire or niobium substrates produced the following results: Films on sapphire, crystallized at 450°C, were equiaxed and had

average grain sizes of ~ 125 Å. However, in these films there were large regions of non-crystallized material which sharply degraded the superconducting properties. Essentially complete crystallization was obtained at 600°C. In the latter case, the microstructure again consisted of equiaxed grains, however with a larger average grain size of ~ 275 Å. An indication of the importance of the substrate material was obtained from observing films on the niobium substrates. Although annealed under similar conditions as the NbN on sapphire, these films showed a columnar microstructure with average diameter of the columns being over 1000 Å. This indicated the ability of a substrate material to significantly influence crystal growth of the X-ray amorphous NbN. Such effect could have importance in the new Westinghouse-AFOSR program dealing with materials for Josephson device applications. Therefore further annealing and TEM studies of films prepared by this method will continue.

4.2.2 E-Beam Annealed Nb_3Ge

Some limited success in preparing ultrafine-grained microstructures was obtained by pulse-annealing technique. The microstructures of e-beam annealed Nb_3Ge films were observed using both TEM and scanning transmission electron microscopy (STEM). Pulse energy, E_p, thresholds for film melting were found to depend strongly on the nature of the film substrate, with films on Nb melting at ~ 40% lower energy. Films annealed only slightly above the melting threshold were less damaged by cracking, blow-off, etc. than those annealed at high E_p's (> 1 joule/cm^2), and could be investigated further. The melted layer was found to resolidify into an ultrafine-grained microstructure with an average grain size of 20 to 40 Å, thus comparable to the coherence length in Nb_3Ge. In situ annealing in the microscope permitted one to directly observe the growth of these micrograins and to prove by electron diffraction that the ultrafine-grained phase was an A15. Elimination of film cracking by preheating of specimens would make e-beam annealing an ideal tool for investigating the correlation between the grain size and global flux pinning force. The use of heated stage in the PEBA apparatus, however, made it impossible to attain E_p values necessary for melting. Further modification and

upgrading would be necessary to make this a viable method for making the desired microstructures.

4.3 The Effect on T_c of Variations in Grain Size

Speculative theoretical arguments have been presented from time to time suggesting that enhanced T_c's may be obtained by reducing the grain size of a superconductor. In a United States patent (#4,050,147) published late in 1977, experimental verification of these ideas seemed to have been otained. The patent claimed that dramatic increases in T_c and H_{c2} for both A15 and B1 structure compounds were achieved by decreasing their grain sizes to ~ 100 Å. A theoretical evaluation of these claims was made and they were judged not believable. Experimental work performed during this program confirmed the validity of this judgment. The T_c's of NbN films which had grain sizes of 100 Å or less were found to be the same or slightly lower than those of films having larger grains. In essence, there was no evidence obtained in this program indicating any enhancement of T_c due to reduced grain size in high-T_c type II superconductors.

4.4 Correlation of Mechanical Load Properties and Microstructure

The mechanical load properties of CVD Nb_3Ge and sputtered NbN films were measured. The measurement was done by simultaneously applying current, perpendicular magnetic field, and uniaxial tensile strain to the sample. The behavior of the Nb_3Ge was found to be qualitatively similar to that of Nb_3Sn. The Nb_3Ge showed a reversible critical current strain-dependence which increased with increasing magnetic field and conformed to Ekin's scaling law. The NbN on the other hand showed no reversible dependence on strain in all fields measured up to 22T. Although it had no influence on the reversible strain properties, the microstructure of the NbN was found to have an effect on the irreversible properties. Irreversible degradation of current with strain occurs in a material as the result of the superconductor beginning to break up. This was observed at a greater strain level in a thin ultrafine-grained film compared to a

thicker film having larger grains. In the thin NbN films the irreversible J_c degradation in the NbN deposited on Hastelloy began at an intrinsic strain of 0.5%. Irreversible degradation of similar films on niobium did not begin until an intrinsic tensile strain of $\epsilon_0 = 1.5\%$. Since the degradation could be correlated to the yield points of the Hastelloy and niobium substrates, these results indicate that the maximum obtainable value for NbN is determined by the yielding of the substrate material. The value of 1.5% is the highest measured for any superconductor to date.

4.5 Other Topics

Other results obtained in the general effort to advance the understanding of high-T_c superconductors are described in the following subsections.

4.5.1 Stabilization of High-T_c Phases

Both of the high-T_c superconductors (Nb_3Ge and NbN) which were primarily used in this program to obtain data on microstructural effects require some stabilization mechanism which permits their formation at low (< 1000°C) temperatures. To aid in sample preparation and also because of the general importance of understanding high-T_c metastable superconductor formation, a significant level of effort in this program was expended to try to identify the mechanisms involved in the low temperature growth of these compounds. In both cases, experimental data indicated the necessity of incorporating some impurity (usually oxygen) into the film during the growth process. It was hypothesized that in the case of Nb_3Ge, the oxygen present near the film-substrate interface stabilizes the Nb_3Ge near the substrate film interface. Chemical analyses show that as the film thickness increases, the oxygen level decreases. However the Nb_3Ge continues to grow with or without oxygen in a metastable form via a "homo-epitaxial" process. The T_c of the film near the interface is low because of the oxygen presence. The T_c of the metastable Nb_3Ge which has little or no oxygen has a very high critical temperature of 22K or higher. In the case of NbN it was proposed that this compound, when prepared at

low temperatures, is actually a stable pseudo-binary with the stabilizing impurity (oxygen, carbon, or both) incorporated into the B1 structure.

Although complete experimental verifications of the above oxygen stabilization hypotheses are still lacking, the need for having oxygen present during the growth of Nb_3Ge is now generally accepted. In an attempt to determine whether oxygen plays some role in the growth of the other high-T_c A15 superconductors, a series of the Nb- and V-based A15 compounds were sputtered in the presence of oxygen. All of the films which had the A_3B composition, were found to have T_c's close to the maximum reported value for each of the compounds. The most interesting aspect of the T_c data, however, was the finding of very high T_c's in A-rich (i.e. $A/B > 3$) films whose average compositions were far removed from ideal 3/1 stoichiometry. These results were seen in both the stable (Nb_3Sn and V_3Si) and unstable (Nb_3Ge, Nb_3Ga, and Nb_3Al) compounds. These data imply that a mechanism (or mechanisms) must be operating which causes the growth of a 3/1 A15 phase in an environment in which the average A/B ratio is > 3. A possible mechanism was proposed which involves an intermediate A-oxide reacting with the B element to form the A_3B compound via a diffusion reaction.

4.5.2 AC Losses — Experimental

The ac losses in in-situ Cu-Nb_3Sn and Cu-V_3Ga composite conductors were determined and found to be very high, approaching those of bulk superconductors. Analysis of results indicated that conductors containing low volume fractions of superconductor and those having short filaments would have relatively lower ac losses. The possibility of in-situ filaments decoupling in very strong magnetic fields, and the effect of twisting on ac losses, have also been investigated. Twisting was found to be rather ineffective. Decoupling by proximity-effect quenching was not observed.

4.5.3 AC Losses — Theory

The ac loss in a multifilament superconducting wire for small ac fields superimposed on a constant bias field was treated theoretically.

This work extended previous treatments to encompass a full range of ac fields up to the field for full penetration. The results contributed to an understanding of experiments and allowed an accurate prediction of losses. End effects on the losses in short filamentary superconductors were also studied.

4.5.4 Ultrasonic Attenuation in Granular NbN Films

Some of the NbN films prepared in this program meet the criteria for granular superconductors as indicated by their void-type microstructure, very high normal state resistivities, and negative resistance ratios. The possibility of using ultrasonic attenuation as a new tool to investigate granular superconductivity was investigated in collaboration with Prof. M. Levy of the University of Wisconsin at Milwaukee. The measured attenuation of surface acoustic wave propagation in these films was found indeed to be anomalous for the superconducting state. A theoretical treatment using the Kosterlitz-Thouless vortex-antivortex pairs provided a semi-quantitative explanation of the data.

4.5.5 Pseudo-Binary V-Si-C Films by Sputtering and Ion Implantation

Based on empirical data relating molecular volume to T_c, there is reason to believe that certain pseudo-binary A15 compounds might have a higher T_c than the binary compound. An example of this seemed to have been found a few years ago when a T_c of over 20K was reported for a V_3(Si-C) pseudo-binary; however, this was never independently confirmed. An attempt was made to confirm that result in this program by sputtering a series of V-Si films with a wide range of V/Si ratios. Into these films carbon was implanted so that there was a Gaussian-like depth profile of carbon concentration. This produced a wide variety of V-Si-C compositions encompassing those reported in the literature as having T_c greater than 20K. All of the films were then annealed at temperatures up to 1000°C. Although there was evidence that carbon was incorporated into the A15 structure, no T_c's greater than that of V_3Si (17.1K) were found. Analysis of the films indicated, however, the presence of significant levels of oxygen in the films. For this reason these results cannot be considered

as definitive on the subject of enhanced T_c's in the V-Si-C pseudo-binary compounds. A useful and somewhat unexpected result from this work was the insight gained on the influence of oxygen on the low temperature growth of stable A15 compounds such as V_3Si. This stimulated work on the effect of oxygen on the low temperature formation of all the known high-T_c compounds. This work leading to the concept of low-temperature synthesis via the formation of intermediate phases was discussed in Section [illegible].

4.5.6 New UHV Deposition-Analytical Facility

The Westinghouse R&D Center has committed itself to the purchase (at no cost to AFOSR) of a new UHV Deposition-Analytical Facility for use in the new Westinghouse-AFOSR program which will focus on the investigation of materials for Josephson device applications. During 1982, conceptual designs were developed and various vendors evaluated. As conceptually constituted, the facility will have the option of depositing films by either evaporation or by magnetron sputtering. The *in-situ* analyses of the films will be by electron diffraction, XPS and Auger. Other capabilities will include plasma oxidation and annealing. The delivery by "Instruments SA/Riber: is scheduled for July 1983.

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14. "Ultrasonic Attenuation by a Thin Film of High Transition Temperature Nb_3Ge," H. L. Salvo, H. P. Fredricksen, M. Levy and J. R. Gavaler, Sol. State Comm., 33: 781 (1980).

15. "High-T_c Superconducting Films," J. R. Gavaler, J. Vac. Science and Tech. 18: 247 (1981).

16. "Dimensional Effects on Current and Field Properties in NbN Films," J. R. Gavaler, A. T. Santhanam, A. I. Braginski, M. Ashkin and M. A. Janocko, IEEE Trans. on Magnetics, MAG-17: 573 (1981).

17. "Ultrasonic Surface Acoustic Wave Investigation of Thin Films of Superconducting NbN," Hans Fredricksen, Moises Levy, J. R. Gavaler and M. Ashkin, IEEE Trans. on Magnetics, MAG-17: 1091 (1981).

18. "In-Situ Formed Multifilamentary Composites, Part II: AC Losses," A. I. Braginski and G. R. Wagner, IEEE Trans. on Magnetics, MAG-17: 245 (1981).

19. "The Effect of Laser Annealing on the Critical Current Density in Nb_3Ge," A. I. Braginski, J. R. Gavaler, R. C. Kuznicki, B. R. Appleton and C. W. White, Appl. Phys. Lett. (July 15, 1981).

20. "Chemical Vapor Deposition of Superconductors," A. I. Braginski, (Extended Summary) Proc. VIII International CVD Conference, Electrochem. Soc. Proc., 81(7): 755 (1981).

21. "Current Distribution Near the End of a Filamentary Superconductor," W. J. Carr, Jr., IEEE Trans., MAG-17: 3435 (1981).

22. "Workshop on Superconductors for Magnets: Frontiers of Technology," A. I. Braginski, H. C. Freyhardt, R. Flükiger, H. Hillmann, D. C. Larbalestier, M. Suenaga and M. N. Wilson, IEEE Trans. on Magnetics, MAG-17: 2343 (1981).

23. "Superconductive Quenching of Piezoelectric Induced Surface Wave Attenuation," H. P. Fredricksen, M. Levy and J. R. Gavaler, Proc. of 16th International Low Temp. Conf. (LT-16): 113 (1981).

24. "Possible Ultrasonic Evidence for the Existence of Vortex-Antivortex Pairs," Hans P. Fredricksen, Moises Levy, M. Ashkin and J.R. Gavaler, Molecular Crystals and Liquid Crystals (in press).

25. "Surface Acoustic Wave Determination of the Superconducting Fraction of a Nb_3Ge Film," Harry Salvo, Jr., Hans P. Fredricksen, Moises Levy and J. R. Gavaler, J. Low Temp. Phys. 48, 189 (1982).

26. "Superconducting Critical Temperatures of C-Implanted A15 Structure V-Si," J. R. Gavaler, A. I. Braginski, A. S. Manocha, B. R. Appleton, C. W. White and J. M. Williams, Metastable Formation by Ion Implantation, S. T. Picraux and W. J. Choyke, Ed., Elsevier North Holland, Ind. (1982), p. 287.

27. "End Effects on the Loss for Short Filamentary Superconductors," W. J. Carr, Jr., Adv. Cry. Eng., Vol. 28 (1982).

28. "Effect of Strain on the Critical Current and Critical Field of B1 Structure NbN Superconductor," J. W. Ekin, J. R. Gavaler and J. Greggi, Appl. Phys. Lett. 41, 996 (1982).

29. "Alternating Current Losses in Twisted In-Situ Composite Wires," A. I. Braginski and J. Bevk, Filamentary A15 Superconductors, M. Suenaga and A. F. Clark, Eds., Plenum Press, N.Y., 1980, p. 321.

30. "The Effect of Oxygen on the Low Temperature Growth of the High-T_c A15 Superconductors," J. R. Gavaler, A. I. Braginski, M. A. Janocko and A. S. Manocha, 4th Conf. on "Superconductivity in d- and f-Band Metals," 1982, Eds., W. Buckel and W. Weber, Kernforschungszentrum Karlsruhe, FRB, p. 35.

31. "The Ultrasonic Attenuation of 700 mHz Surface Acoustic Waves in Thin Films of Superconducting NbN," H. P. Fredricksen, M. Levy, J. R. Gavaler and M. Ashkin, Accepted for publication in Phys. Rev B.

32. "Ultrasonic Attenuation Determination of Superconducting Energy Gap Anomolies in Thin Films of NbN," Hans P. Fredricksen, M. Levy, M. Tachiki, M. Ashkin and J. R. Gavaler, To be published in IEEE Ultrasonic Symposium (October 1982), San Diego.

33. "Properties of NbN Films Crystallized from the Amorphous State," J. R. Gavaler, J. Greggi, R. Wilmer and J. W. Ekin, To be published in Proceedings of the 1982 Applied Superconductivity Conference.

34. "Pulsed Electron-Beam Annealing of Nb-Ge Films," A. I. Braginski, J. Greggi, M. A. Janocko and O. Meyer, To be submitted to J. Appl. Phys.

35. "Origin of 440 Kilogauss Upper Critical Field in NbN Films," M. Ashkin, J. R. Gavaler, J. Greggi and M. Decroux, In preparation.

6. PERSONNEL CONTRIBUTING TO PROGRAM

M. Ashkin

A. I. Braginski

W. J. Carr, Jr.

J. R. Gavaler

J. Greggi

M. A. Janocko

A. S. Manocha

G. W. Roland

A. T. Santhanam

G. R. Wagner

7. COUPLING ACTIVITIES*

1. "Preparation of A15 Superconductors by Liquid Sodium Reduction," R. G. Charles and J. R. Gavaler, contributed talk APS Meeting, Washington, DC (March 1978).

2. "The Upper Critical Field of NbN Film," M. Ashkin and J. R. Gavaler, contributed talk, APS Meeting, Washington, DC (March 1978).

3. "Assessment of Reported Enhanced Superconducting Properties of Small Particles Dispersed in a Metallic Matrix," M. Ashkin and A. I. Braginski, contributed paper, Am. Phys. Soc. Meeting, Washington, DC, March 27-30, 1978.

4. "The Dependence of Critical-Current Density in Nb_3Ge Upon the Film Thickness and Grain Size," A. I. Braginski, G. W. Roland and A. T. Santhanam, contributed talk, Am. Phys. Soc. Meeting, Washington, DC, March 27-30, 1978.

5. "Superconducting Materials Research at Westinghouse," A. I. Braginski, invited seminar at the Karlsruhe Nuclear Center, Institute for Technical Physics, Karlsruhe (West Germany), April 25, 1978.

6. "Flux Pinning in Nb_3Ge," A. I. Braginski, seminar at the Siemens Research Laboratories in Erlangen (West Germany), April 28, 1978.

7. "Superconducting Nb_3Ge for High-Field Magnets," contributed talk, A. I. Braginski, M. R. Daniel, G. W. Roland and J. A. Woollam, The 1978 Intermag Conference, Florence (Italy), May 9-12, 1978.

8. "Stabilization of High-T_c Nb_3Ge," J. R. Gavaler, M. Ashkin, A. I. Braginski and A. T. Santhanam, Poster paper at Low Temp. Phys. Conf., LT15, Grenoble, France (August 1978) (presented by R. Hein).

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*Name of the speaker is underlined.

9. "Properties of Reactively Sputtered Superconducting Films," J. R. Gavaler, contributed talk, Appl. Supercond. Conf., Pittsburgh, PA (Sept. 1978).

10. "Microstructure Control in Nb_3Ge and Its Effect Upon the Critical-Current Density," A. I. Braginski, G. W. Roland and A. T. Santhanam, contributed talk, Appl. Supercond. Conf., Pittsburgh, PA (Sept. 1978).

11. Effect of Strain on the Critical Current of Nb_3Ge," J. W. Ekin and A. I. Braginski, contributed talk, Appl. Supercond. Conf., Pittsburgh, PA (Sept. 1978).

12. "AC Losses in "In-Situ" Nb_3Sn-Cu Composite Conductors," A. I. Braginski, G. R. Wagner, J. Bevk and J. P. Harbison, contributed talk, Appl. Supercond. Conf., Pittsburgh, PA (Sept. 1978).

13. "Studies of Electron Beam Co-Evaporated Nb_3Sn Composites," R. H. Hammond, B. E. Jacobson, T. H. Geballe, J. Talvacchio, J. R. Salem, H. C. Pohl and A. I. Braginski, contributed talk, Appl. Supercond. Conf., Pittsburgh, PA (Sept. 1978).

14. "Phase Stability of Nb_3Ge," M. Ashkin, Seminar at the University of Wisconsin-Milwaukee, November 13, 1978.

15. Round table discussion among R. Roy and colleagues of Penn State University and J. R. Gavaler, M. Ashkin and A. I. Braginski, on Superconducting Material Research (at Penn State University, November 22, 1978).

16. Round table discussion among W. Appleton and colleagues of Oak Ridge National Laboratory and A. I. Braginski, M. Ashkin and J. R. Gavaler, on new fabrication techniques for preparing superconductors (at Oak Ridge, December 12, 1978).

17. "Properties of High-T_c Superconducting Thin Films," J. R. Gavaler, Seminar at the University of Wisconsin-Milwaukee, March 1979.

18. "Ultrasonic Surface Wave Attenuation in Nb_3Ge Film," H. Salvo, H. Fredricksen, M. Levy, and J. R. Gavaler, contributed talk APS Meeting, Chicago, Ill. (March 1979).

19. "Upper Critical Fields of NbN and Nb-C-N Films," J. R. Gavaler, contributed talk, APS Meeting, Chicago, Ill. (March [illegible]).

20. "Applications of Superconductivity," M. Ashkin, Seminar at Air Force Institute of Technology (AFIT), Wright-Patterson Air Force Base, Ohio, (May 17, 1979).

21. "Thin Films and Metastable Phases," J. R. Gavaler, A. I. Braginski M. Ashkin, and A. I. Santhanam, invited talk, 3rd Conf. on Superconductivity in d- and f-Band Metals, La Jolla, Calif. (June 1979).

22. "AC Losses in Untwisted Composites Fabricated by an 'In-Situ' Technique," A. I. Braginski, G. R. Wagner and J. Bevk, contributed talk at the 1979 ICMC Conf., Madison, Wis. (Aug. 1979).

23. "Cu-V_3-Ga 'In-Situ' Superconducting Composites: A Review," J. Bevk, F. Habbal and A. I. Braginski, AIME Conf. Sept. 16-20, 1979, Milwaukee, Wis.

24. "AC Properties of 'In-Situ' Composites," A. I. Braginski, Seminar at the Nuclear Center, Karlsruhe, West Germany (Oct. 10, 1979).

25. "Losses in Nb_3Sn-Cu 'In-Situ' Composites," A. I. Braginski, Seminar at the Siemens Research Center, Erlangen, West Germany, (Oct. 26, 1979).

26. Participation in a discussion of flux pinning in A15's at the 7th Materials Colloquium, Univ. of Erlangen, Nurnberg, West Germany, A. I. Braginski, (Oct. 30, 1979).

27. Participation in Conf. on In-homogeneous Superconductors," J. R. Gavaler, Berkeley Springs, W.V., (Nov. 1-3, 1979).

28. "Ion Implantation and Laser Annealing of High T_c Superconducting Materials," B. R. Appleton, C. W. White, B. Stritzker, O. Meyer, J. R. Gavaler, A. I. Braginski and M. Ashkin, contributed talk in the Symposium on Laser and Electron Beam Processing of Materials, Materials Research Society, Annual Meeting, Cambridge, Mass., (Nov. 26-30, 1979).

29. "Stabilization Mechanisms of Metastable Nb_3Ge," A. I. Braginski, Seminar at the Nuclear Center, Karlsruhe, West Germany (Nov. [illegible], 1979).

30. "AC Losses in 'In-Situ' Composites," A. I. Braginski, Seminar at the Univ. of Geneva, Switzerland, (Dec. 11, 1979).

31. " 'In-Situ' Composites and their AC Properties," A. I. Braginski, Seminar of the Atomic Institute of Austrian Universities, Vienna, Austria (Nov. 16, 1979).

32. "Laser Annealing of High-T_c Superconducting Materials," J. R. Gavaler, A. I. Braginski, M. Ashkin, B. R. Appleton and C. W. White, contributed paper (HG6) at the 1980 March Meeting of Am. Phys. Society.

33. "Flux Distribution and Hysteresis Loss in a Round Superconducting Wire in a Transverse Field," M. Ashkin, contributed paper (KG11) at the 1980 March Meeting of Am. Phys. Society.

34. "Proximity Effect Observed in Hysteretic Loss Behavior of 'In-Situ' Cu-Nb_3Sn," A. I. Braginski and J. Bevk, contributed paper (KG12) at the 1980 March Meeting of Am. Phys. Society.

35. "Alternating Current Losses in Twisted 'In-Situ' Composite Wires," A. I. Braginski and J. Bevk, paper presented at the 1980 ICMC on A15 Filamentary Superconductors, May 28-29, 1980.

36. Discussion meeting on stabilization of high-T_c A15 phase, A. I. Braginski, P. Chaudhari and C. C. Tsuei, IBM Research Center, March 4, 1980.

37. "Dimensional Effects on Current and Field Properties in NbN Films," J. R. Gavaler, A. T. Santhanam, A. I. Braginski, M. Ashkin and M. A. Janocko, Contributed paper presented at the Applied Supercon. Conf., Santa Fe, NM (Sept. 1980).

38. "*In-Situ* Found Multifilamentary Composites, Part II: AC Losses," A. I. Braginski and G. R. Wagner, Invited paper presented at 1980 Applied Superconductivity Conf., Santa Fe, NM (Sept. 1980).

39. "Ultrasonic Surface Acoustic Wave Investigation of Thin Films of Superconducting NbN," Hans Fredricksen, M. Levy, J. R. Gavaler and M. Ashkin, Contributed paper presented at the Applied Superconductivity Conference, Santa Fe, NM (September 1980).

40. "High-T_c Superconducting Films," J. R. Gavaler, Invited paper presented at the American Vacuum Society Meeting, Detroit, MI (October 1980).

41. "The Effect of Laser Annealing on the Critical Current Density of Nb_3Ge," A. I. Braginski, J. R. Gavaler, B. R. Appleton and C. W. White, contributed paper presented at the A. P. S. Spring Meeting, Phoenix, AZ (March 1981).

42. "Critical Temperature of A15 Structure V-Si-C Films," J. R. Gavaler, A. I. Braginski, B. R. Appleton, C. W. White and J. M. Williams, contributed paper presented at the A. P. S. Spring Meeting, Phoenix, AZ (March 1981).

43. "Workshop on Superconductors for Magnets: Frontiers of Technology," organized and chaired by A. I. Braginski at the 7th International Magnet Conference, Karlsruhe, West Germany, March 30-April 3, 1981.

44. "Superconductors for High Field Magnets," a seminar given by A. I. Braginski at the Grenoble Nuclear Center, France, on May 4, 1981.

45. "AC Losses in 'In-Situ' Composites," a seminar given by A. I. Braginski at the Saclay Nuclear Center, France, on May 7, 1981.

46. "Current Distribution Near the End of a Filamentary Superconductor," a contributed paper presented by W. J. Carr, Jr. at the 1981 Intermag Conference in Grenoble, France, May 15, 1981.

47. "Possible Ultrasonic Evidence for the Existence of Vortex-Antivortex Pairs," Hans P. Fredricksen, M. Levy, M. Ashkin and J. R. Gavaler, Contributed paper presented at the International Conf. on Low Dimensional Conductors, Boulder, Colorado, August 1981.

48. "Superconducting Quenching of Piezoelectric Induced Surface Wave Attenuation," H. P. Fredricksen, M. Levy and J. R. Gavaler, Contributed paper presented at 16th International Low Temp. Phys. Conf. (LT-16) Los Angeles, CA, August 1981.

49. "The Effect of Laser and Electron Annealing on the Critical Current Density of Nb_3Ge," A. I. Braginski, J. R. Gavaler, J. Greggi, R. C. Kuznicki, M. D. Nahemow, B. R. Appleton, C. W. White and J. M. Williams, Contributed paper presented at the CEC-ICMC Conf, San Diego, CA, August 1981.

50. "End Effects on the Loss for Short Filamentary Superconductors," W. J. Carr, Jr., Contributed paper presented at the CEC-ICMC Conf., San Diego, CA, August 1981.

51. "Chemical Vapor Deposition of Superconductors," A. I. Braginski, Invited paper presented at the VIII International CVD Conference, Gouvieux, France, September 1981.

52. "Superconducting Critical Temperatures of A15 Structure V-Si," J. R. Gavaler, A. I. Braginski, A. S. Manocha, B. R. Appleton, C. W. White and J. M. Williams, Contributed paper presented at the Material Research Conf., Boston, MA, November 1981.

53. "Pulsed Electron-Beam Annealing of Nb-Ge Films," A. I. Braginski, J. Greggi, M. A. Janocko and O. Meyer, APS Spring Meeting Dallas, Texas (March, 1982).

54. "Effect of Strain on the Critical Current of Sputtered NbN Films," J. W. Ekin, J. R. Gavaler and J. Greggi, APS Spring Meeting Dallas, Texas (March, 1982).

55. "The Effect of Oxygen on the Low Temperature Growth of the High-T_c A15 Superconductors," J. R. Gavaler, A. I. Braginski, M. A. Janocko and A. S. Manocha, presented at the 4th Conf. on Superconductivity in d- and f-Band Metals, Karlsruhe, FRG (June, 1982).

56. "Properties of NbN Films Crystallized from the Amorphous State," J. R. Gavaler, J. Greggi, R. Wilmer and J. W. Ekin, Appl. Supercon. Conf., Knoxville, TN (November, 1982).

57. "Origin of 440 Kilogauss Upper Critical Field in NbN Film," M. Ashkin, J. R. Gavaler, J. Greggi and M. Decroux, Material Research Society Meeting, Boston, MA (November, 1982).

58. "Role of Intermediate Oxide Phases in the Formation of A15 Superconducting Film," J. R. Gavaler, A. I. Braginski, M. A. Janocko, A. S. Manocha, W. Schauer and F. Wüchner, Material Research Society Meeting, Boston, MA (November, 1982).

59. "Ultrasonic Attenuation Determination of Superconducting Energy Gap Anomolies in Thin Films of NbN," H. P. Fredricksen, M. Levy, M. Tachiki, M. Ashkin and J. R. Gavaler, contributed paper IEEE Ultrasonic Symposium (October, 1982) San Diego, CA.

60. "Discussions on the Role of Oxygen in the Growth of A15 Superconductors," A. I. Braginski, NATO School on Advances in Superconductivity, Erice, Italy (July, 1982).

8. PATENTS AND INVENTIONS

1. "A High-T_c Multifilamentary Superconducting Composite Conductor with Superior Mechanical Properties," J. R. Gavaler, Westinghouse Patent Disclosure (June 2, 1982).

2. "B1 Crystal Structures for Application in Strain Environments," J. W. Ekin, J. R. Gavaler and J. Greggi, Patent Disclosure submitted at NBS (by JWE) and Westinghouse (by JRG and JG).

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